Josephson Plasma Excitation and Vortex Oscillation Mode in Josephson Vortes State

I. Kakeya, T. Wada, and K. Kadowaki

Institute of Materials Science, University of Tsukuba, Tsukuba, Ibaraki 305-8573 Japan

M. Machida

Japan Atomic Energy Research Institute, 2-2-54 Nakameguro, Meguro-ku Tokyo 153-0061, Japan

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The Josephson plasma resonance has been investigated in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals in parallel magnetic fields to the ab-plane. We found two resonance modes; one appears at higher frequency in high fields above the plasma frequency ω_p at zero field and absolute zero, and the other lies below ω_p and is observed only in magnetic fields without considerable field dependence. Two resonance lines were also found in numerical simulations in a single junction model with randomness of the critical current. The higher frequency mode is attributed to the Josephson plasma mode modified by the periodic structure of Josephson vortices, while the lower frequency mode is interpreted as oscillations of Josephson vortices.

74.60.Ge, 74.50.+r, 74.25.Nf, 72.30.+q

I. INTRODUCTION

When the external magnetic field is applied parallel to the ab-plane of high-T_c superconductors such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO), Josephson vortices penetrate into block layers. Since the phase difference between two adjacent CuO_2 layers which confine a Josephson vortex is π, the Josephson vortex is a good example of non-linear dynamics in superconductors. Dynamical properties of Josephson vortices are strongly affected by the Josephson plasma because the Josephson vortex and the Josephson plasma are solutions of the non-linear and linear part of the sine-Gordon equation[1]. Furthermore, a strong emission of electromagnetic wave is expected when the velocity of the JV lattice matches the Josephson plasma wave velocity[2]. Therefore, the Josephson plasma resonance in the presence of the Josephson vortices is very powerful tool to reveal dynamical nature of the Josephson vortices.

The Josephson plasma resonance (JPR) is known to manifest the existence of weakly coupled Josephson effects between CuO_2 layers sandwitched by the non-superconducting or insulating block layers. In particular, in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO), which is a typical high-T_c superconductor and possesses an intrinsic high anisotropy due to extremely weak Josephson coupling, the plasma frequency $\omega_p \equiv c/\sqrt{\epsilon}\lambda_c$ can be as low as 100 GHz, where ϵ and λ_c are the dielectric constant and the c-axis penetration depth. Absence of the Landau damping of the quasiparticles in addition allows us to observe extremely sharp resonance at microwave frequencies using conventional high sensitive microwave techniques[3]. The plasma frequency in a magnetic field parallel to the c-axis can be expressed as a function of field and temperature: $\omega_p^2(H,T) = \omega_p^2 \langle \cos\varphi_{l,l+1}(H,T) \rangle$, where $\varphi_{l,l+1}$ is the gauge invariant phase difference between adjacent l and $l+1$-th layers and $\langle \cdots \rangle$ denotes spatial and thermal averages[4]. This means that $\omega_p(H,T)$ can directly sense the interlayer phase coherence in a dynamical manner,

which is severely influenced by the thermal fluctuation of vortices. Thus, ω_p in general should decrease with increasing field at a given temperature. Especially in the vortex liquid state, ω_p is expected to follow $H^{-1/2}$ as reported previously[5–7].

In contrast to this, the Josephson plasma in fields parallel to the ab plane is much more complicated because of the non-linear behavior of the Josephson vortex as mentioned above. In the case of single junctions, the excitation spectrum in the presence of Josephson vortices has been studied by Fetter and Stephen[8] for example. They derived an excitation spectrum with two branches: one is the gapless *vortex* branch attributed to the dc sliding mode of JVs, and the other is the *plasma* branch identical to the transverse Josephson plasma, which monotonically increases with increasing field.

In a layered system having a multi-stack of the intrinsic Josephson junctions like in BSCCO, however, physics becomes richer, because it allows us to observe the longitudinal plasma mode (Nambu-Goldstone mode) that the coherence length comparable to the interlayer distance, and the Josephson plasma can propagate not only as the transverse wave but also as the longitudinal wave or their mixtures. Furthermore, the 2D lattice of JVs may be realized and the properties may be strongly affected by the intrinsic pinning. Although much progress of the theories for the dynamical properties of JVs[2,9], experimental development has been hindered due partly to the experimental difficulties restricted by precise magnetic field alignment to the ab-plane of the crystal, which requires its extremely high quality. Concerning the Josephson plasma in parallel fields, systematic experimental study in order to understand whole spectrum of physical properties of the Josephson plasma has not been performed, although some preliminary work of JPR in parallel fields to the ab-plane were reported by Matsuda *et al.*[10].

In this paper, we present our results of JPR measurements in parallel fields to the ab-plane as functions of microwave frequency, field intensity, and temperature in

order to reveal the entire nature of the Josephson plasma in the presence of JVs. As a result, we obtained two resonance branches, which are separated by a finite gap in good accordance with the recent theoretical approaches. One observed at higher frequencies is attributed to the Josephson plasma coupled with the JV lattice, while the other lying at lower frequencies is interpreted due to the vortex oscillation mode hardened by residual pinning.

II. EXPERIMENTS

We used an under-doped BSCCO single crystal grown by the modified traveling solvent floating zone method. The under-doped crystal was obtained after annealing at 550 °C for 12 hours in a vacuum. The superconducting transition temperature T_c of this crystal was determined to be 70.2 K by magnetization measurements with a SQUID magnetometer. JPR measurements have been performed in a microwave frequency range between 9.8 and 75 GHz with both reflective and transmission type of bridge balance circuits with rectangular TE_{102} mode cavity resonators. The sample was placed inside the cavity so that the oscillating electric field E_{rf} is exerted parallel to the c-axis to selectively excite the longitudinal plasma mode[11]. A frequency-stabilized microwave was generated by the signal swept generator (HP83650B) or the Gunn oscillators, and the resonance was detected as changes of cavity impedance (Q-factor) either by field sweep or by temperature sweep. The magnetic field was applied by a split-pair of superconducting magnet, which can generate horizontal magnetic fields up to 8 T and the angle between field direction and crystal axis was changed by rotating the cavity resonator with respect to the magnet by a precision goniometer. The field direction exactly parallel to the ab-plane was determined by looking at the symmetry of the angular dependence of the resonance within an accuracy of 0.01 degree.

III. RESULTS AND DISCUSSION

Figures 1 (a) and (b) show the resonance curves at 18.9 and 25.5 GHz, respectively, obtained by sweeping temperature. Clear two resonance lines without hysteresis at higher and lower temperatures, and a temperature gap in between the two resonances are found at both frequencies. As the field is increased, the resonance at higher temperatures once shifts to lower temperatures, then turns to shift to higher temperatures above 1 kOe. It is finally smeared out above 1.5 kOe, while the resonance at lower temperatures appears at around 1 kOe from lower temperature side and shifts to lower temperatures with little change its line-shape. Hereafter, we call these resonances at higher and lower temperatures HTB (higher temperature branch) and LTB (lower temperature branch), respectively. The fact that two lines

are observed and the resonance temperature of HTB increases as the field is increased is peculiar in comparison with the case in fields parallel to the c axis. It is noted that the LTB resonance obtained by *field* sweep was not considered here, because it showed large hysteresis and moreover the line-width was too wide due to the pinning effect.

As the frequency is increased, these two resonance lines shift to lower temperatures. Figure 2 represents the summary of resonance peaks as functions of field and temperature for various frequencies. Both HTB and LTB shift to lower temperatures and the gap grows rapidly as the frequency increases. LTB goes beyond our experimental temperature range above 30 GHz as shown in the upper panel of Fig. 1, whereas HTB is obtained at all frequencies. At a frequency below 60 GHz, HTB is observed at zero field at a finite temperature T_0, where the microwave frequency corresponds to the temperature dependent zero-field plasma frequency $\omega_p(T)$. Extrapolating $\omega_p(T)$ to $T = 0$ K, the inherent plasma frequency ω_p can be estimated to be 56.8 GHz. The turning of HTB is more significant at higher frequencies, the resonance temperature above 3 kOe exceeds T_0 above 30 GHz, suggesting that the plasma frequency above 3 kOe may exceed ω_p, whereas LTB just shifts to lower temperatures with increasing frequency. The resonance peak above ω_p is also plotted in the lower panel of Fig. 2. Similarly to HTB, the resonance line above ω_p shows no hysteresis in field sweep experiments even at low temperatures and peaks by sweeping field and temperature correspond well. Furthermore, the resonance shifts to higher temperatures as the field is increased, and is smeared out at higher fields. Thus, it is natural that this resonance is attributed to HTB observed below ω_p.

In order to estimate in-plane field contribution to the Josephson plasma, the plasma frequency as a function of magnetic field is extracted from Fig. 2. In Fig. 3 the plasma frequencies $\omega_p(H)$ divided by the zero-field plasma frequencies $\omega_p(T)$ for various temperatures are shown. It is clearly seen that two resonance modes well-separated by a frequency gap exist: the higher one extracted from HTB shows upturn at about 1 kOe, then monotonically rises to higher frequencies even above ω_p, while the other extracted from LTB shows a gradual decrease with increasing field. It is also found that both are well scaled with $\omega_p(T)$ except for the initial decrease of HTB below 1 kOe. Since LTB can be observed only in a finite field, the existence of JVs would be indispensable for LTB. At low fields below 0.5 kOe, the extrapolation of LTB tends to the zero frequency with decreasing field, suggesting that LTB may be a gapless mode at the zero-field limit. This gives a straightforward interpretation that LTB and HTB are the vortex and the plasma branches as suggested by Fetter and Stephen[8].

Very recently, Koshelev and Machida have developed formulations of layered superconductors in high parallel fields to the ab-plane when a uniform oscillating electric field was applied over the ab-plane parallel to the c-

axis[12]. Assuming that all block layers are fully occupied by JVs, which are forced to make a distorted triangular lattice, they calculated the microwave dissipation due to the Josephson plasma modified by oscillations of the JV lattice. In this case, the Josephson plasma wave propagates an oblique direction along the primitive reciprocal lattice vector of the JV lattice $\mathbf{q}$, which consists of the c-axis component q_c fixed on π/s due to the intrinsic pinning and the ab-plane component q_{ab} proportional to magnetic field H as $2\pi sH/\Phi_0$. The plasma frequency is determined by the dispersion relation along $\mathbf{q}$ lying between the longitudinal and the transverse plasma modes. (Actually, it lies very close to the longitudinal mode because of $q_{ab} \ll q_c$.) As a result, the peak frequency of the dissipation spectrum was obtained to be proportional to the magnetic field parallel to the layers H,

$$\omega_p(H) = \omega_p \frac{\pi H \gamma s^2}{\Phi_0}. \tag{1}$$

Assuming $\gamma = 1070$, which is reasonable for under-doped BSCCO samples, this equation gives an excellent agreement with the experimental data above 3 kOe at all temperatures as shown in Fig. 3, where we used $s = 15$ Å. It denotes that the same equation has derived by Bulaeveskii $et\ al.$ in Ref.[13]. According to Ichioka, all block layers are occupied by JVs above $H^* = \Phi_0/4.6\gamma s^2$[14], which is obtained to be 2.1 kOe for the above-mentioned γ. This is consistent with the fact that the linear field dependence of HTB is violated below 3 kOe as shown in Fig. 3. We therefore conclude that the linear increase of $\omega_p(H)$ of HTB is attributed to the increase of q_{ab} of the JV lattice, while q_c is fixed on π/s because of the intrinsic pinning.

On the other hand, LTB is considered to originate from the oscillations of Josephson vortices, which would be hardened by residual pinning. Figure 4 represents results of numerical simulations on the microwave absorption of the single junction model in the presence of randomness of the c-axis critical current density. Introducing the randomness, which represents pinning center of vortices, a faint peak appears below ω_p. With increasing field, the faint peak does not change while the higher frequency peak shifts to higher frequencies and its intensity becomes weaker. This feature is consistent with the experimental results in the following points: the peak of the LTB resonance does not shift to higher frequency and the HTB resonance is smeared as field is increased. However, the intensity of the low-lying resonance is much fainter than that we observed, the intensity of LTB is rather higher than the one of HTB.

Finally, we comment on the initial decrease of HTB resonance frequency in low fields in connection with the Josephson vortex state. In the low field region, the effect of the JV lattice is not significant yet, so that the thermal fluctuation of vortices may play an important contribution to suppress the Josephson coupling likewise the case of JPR in perpendicular fields. More detailed analysis of this feature is necessary.

IV. CONCLUSION

We have investigated the Josephson plasma mode in parallel fields to the ab-plane of BSCCO. We obtained two resonance modes with a temperature dependent gap in-between. Strong coupling between Josephson plasma and JV lattice are responsible for them. In high fields where all block layers are occupied with JVs, one lying higher frequency comes from the Josephson plasma oscillation modified by the JV lattice, while the other is attributed to the vortex oscillation hardened by pinning of Josephson vortex lattice.

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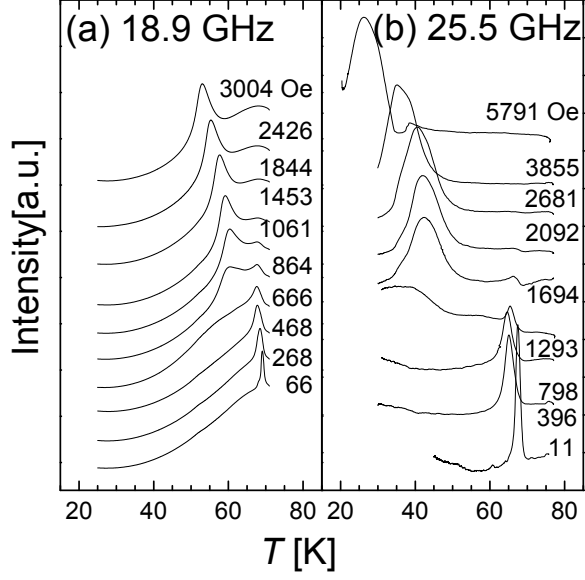[14] M. Ichioka, Phys. Rev. B **51**, 9423 (1995).

FIG. 1. Resonance curves at (a) 18.9 and (b) 25.5 GHz. Temperature was swept from far above T_c to the lowest temperature after changing magnetic field, and no hysteresis was found.
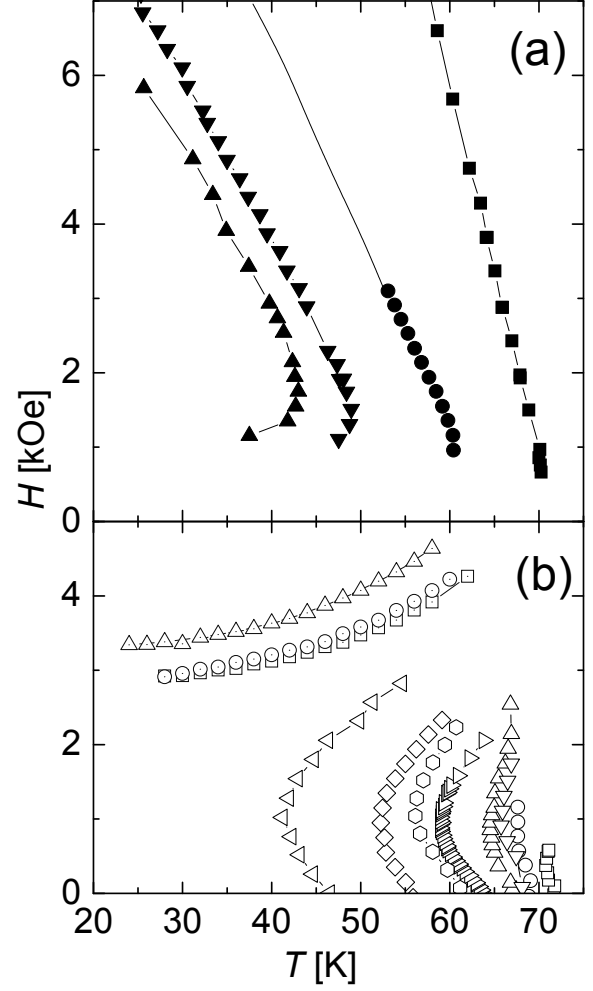

FIG. 2. Field–temperature diagrams of the resonance modes for various frequencies. Solid symbols in (a) indicate LTB obtained by sweeping temperature at 9.8, 18.8, 22.3, and 25.5 GHz and open symbols in (b) indicate HTB at 9.8, 18.8, 22.3, 25.5, 34.5, 39.5, 44.2, and 52.3 GHz from right to left. Open-dotted symbols indicate resonance peaks obtained by sweeping field above ω_p at 61.7, 65.9, and 74.3 GHz from bottom to top.
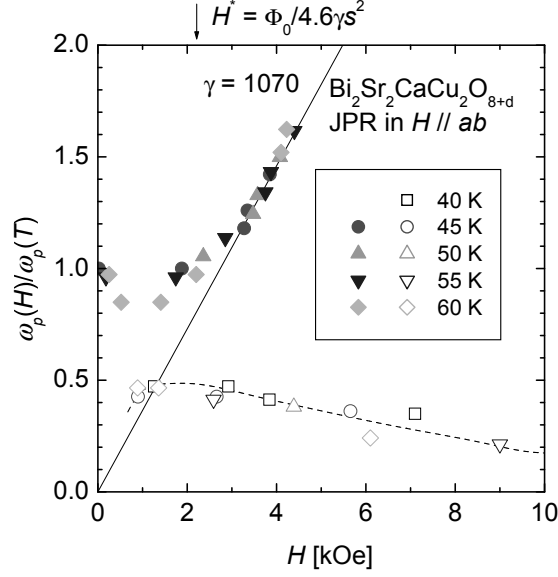
FIG. 3. The frequency-field diagram for HTB and LTB. The plasma frequency $\omega_p(H)$ is normalized by the zero-field plasma frequency $\omega_p(T)$. Solid and open symbols denotes HTB and LTB, respectively. A solid line is given by Eq. (1) with $\gamma = 1070$ and a broken curve is a guide for eyes.
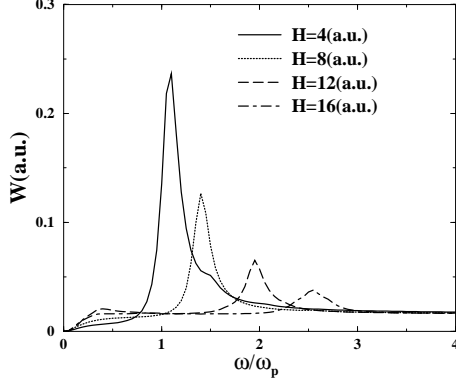

FIG. 4. Results of numerical simulations of the microwave absorptions in the single junction model with randomness of the critical current in four different field intensities. The amplitude of the randomness is constant and the upper-right legend denotes field intensities.